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B70 11059

SUBJECT: The Surface Electrical Properties Experiment - Case 340

DATE: November 27, 1970

FROM: M. T. Yates

ABSTRACT

Three major areas of concern are identified that affect the probability of the Surface Electrical Properties Experiment meeting its objectives:

1. Modeling complex subsurface geometries
2. Specifying an adequate range measurement and a technique to implement it, and
3. A comprehensive error analysis.

Of these the third is the most critical since results of such an analysis could affect the hardware design, while the second may require more astronaut involvement in conducting the experiment.

Various sources are identified which could radiate detectible noise in the megahertz frequency range. These include man-made sources such as the rover, the LM, the CSM, and the traverse gravimeter; and natural sources, e.g., the galactic background, solar storms, and earth's ionosphere. A detailed analysis of these noise sources is required in order to specify realistic measurement accuracies and to evaluate the relative merit of the experiment.

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MEMORANDUM FOR FILE

I. INTRODUCTION

The Surface Electrical Properties Experiment (SEP) is a lunar surface traverse experiment recently approved for development and scheduled to fly on Apollo 17 in mid-1972. Its primary objectives are the search for subsurface layering and the detection of liquid water on the moon. The first of these objectives has obvious significance to our understanding of lunar geology and stratigraphy and is a goal of many of the surface experiments, while the second objective pertains both to discovery of a major geochemical factor and to the most significant natural resource we could find on the moon.

The prospecting technique to be used is radio interferometry: a mobile radio receiver monitors signal strength from a fixed transmitter as a function of range and frequency. The resultant profile is then interpreted in terms of partially reflecting subsurface horizons, which are the desired subsurface layers, and/or a totally reflecting layer which would be a water interface. Application of this technique requires that the lunar material be fairly transparent to radio waves, absorption lengths of 10 wavelengths or more being necessary for adequate signal strengths. While this requirement may be met on the moon (Reference 1), the omnipresence of moisture in earth soils has prevented this technique from becoming a standard geophysical prospecting tool. The purpose of this memorandum, then, is to describe the technique of radio interferometry as applied to depth sounding, the characteristics of its implementation on the moon, as well as some of the interpretation problems that make the SEP an extremely challenging experiment.

II. THE EXPERIMENT

As its name implies, radio interferometry relies on the interaction or interference of two or more radio signals. In astronomical applications the two signals are commonly from the same source (a star) measured at two locations, however in the present application the interference between one source (a transmitter) and virtual images of this source caused by reflections off various interfaces is used to determine the depth of the interface and the reflection coefficients. Figure 1 shows schematically three such signal paths that would result from (say) the regolith - free space interface and the regolith - bedrock interface. The relative phases of these signals will be functions of the distances involved and the electrical properties of the various layers. These characteristics of the lunar subsurface are then determined in the usual way by calculating the theoretical response of various geologic models and comparing this with the experimental data. Uniqueness can never be guaranteed (a failing of most remote sensing techniques) and large amounts of data are needed to limit the possible models to even a crude degree. Nevertheless, prospecting techniques on earth with similar drawbacks (seismic profiling, for example) have proved essential in understanding the structure of the earth's crust.

The hardware presently being designed for the SEP experiment consists of five major subassemblies* (Figure 2):

1) Transmitter: This package (including antennas) weighs about 11 lbs and fits on a 10"x13" pallet space. A solar panel of 1.5 ft^2 (maximum) supplies power which is used to generate frequencies of 0.5, 1, 2, 4, 8, 16, 24, and 32 MHz, as well as lower frequencies used for timing. The radio frequencies are fed through two matched R.F. amplifiers where they are modulated by $\sin(\omega t)$ and $\cos(\omega t)$ functions respectively where ω=15 Hz.

2) Transmitter Antenna Arrays: These are two sets of dipole antennas, one fed by each R.F. amplifier, laid out orthogonally on the lunar surface. Each frequency is radiated from its own half wavelength dipole except for the 0.5 and 1 MHz (the longest antenna is 70 m). The 15 Hz modulation and crossed dipoles produce a transmitted signal which is equivalent to a rotating dipole pattern, and which results in a signal with a 30 Hz modulation detected by the receiver antennas.

3) Receiver Antennas: These consist of three mutually orthogonal loops each about 1 foot in diameter mounted on the end of a 3 foot boom. These loop antennas are sampled sequentially by the receiver.

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*More detailed descriptions may be obtained from "Surface Electrical Properties Experiment, Conceptual Design", MIT Center for Space Research Report CSR TR70-7, October 28, 1970.

4) Receiver: This box is similar in size and weight to the transmitter and is battery powered. It amplifies and detects the signal from the antennas, conditions it, and delivers it to the recorder.

5) Tape Recorder: This recorder is basically the same DSEA recorder presently used on board the LM. It has a capacity of 4 tracks at 2 1/2 hrs each for a total of 10 hrs single track recording. The tape speed is 0.6 inches/sec at a bandwidth of better than 5 KHz. The data format (Figure 2) on the tape has a main frame rate of 1 sec. This 1 sec consists of eight 100 msec intervals each corresponding to the transmitter frequency steps plus 200 msec for frame synchronization. Each 100 msec interval is further subdivided into three 33 msec intervals corresponding to the receiver's sampling of the three receiving antennas. Within each 33 msec interval then is recorded the R.F. field strength modulated by the 30 Hz signal and low pass filtered at about 3 KHz. In addition a synchronizing signal of 5.2 KHz is recorded in order to control the playback rate of the tape. The entire tape recorder is returned to earth for data analysis.

The integration of the SEP into the mission calls for the deployment of the transmitter and the two antenna arrays on the lunar surface at least 200 m from the LM. The receiver is then activated, its antennas unfolded and it is carried either by hand or (preferably) on the rover out along one leg of the transmitter antennas (35 m) stopping every few meters at pre-marked spots on the antennas wires. This will provide an initial calibration baseline of known (although rather short) length. Note that the wavelengths of interest are 10 m corresponding to 32 MHz to 600 m (0.5 MHz). The receiver is then mounted on the rover and the antenna boom extended (if not already done). This boom will raise the receiving antennas to a height of 5 feet or so from the ground in order to have a relatively unobstructed view of the horizon and the lunar surface. No further astronaut involvement is needed until sometime near the end of the EVA when the receiver is turned to standby. The 10 hr tape capacity will allow the experiment to be conducted on both EVA 2 and 3 for the most extensive terrain coverage. At the end of the last EVA the tape recorder is removed from the receiver and stowed in the LM for return to earth. The total time dedicated to the experiment will be 30 man minutes by the most optimistic estimate (MSC). More realistic estimates must await an evaluation of the difficulty of deploying and aligning the dipole antennas.

III. THE INTERPRETATION

For a successful interpretation of the data to be collected during this experiment two separate problems need to be considered: The first and simpler is the theoretical one; this is, the response to radio sounding of realistic models for the lunar subsurface must be calculable (or, at least, estimable), including effects such as scattering from inhomogeneties, rough interfaces, non-sharp discontinuities, lateral multipath, multi-layer models including refractive index inversions and curvature. Much of this theory is well known and calculations for a variety of simple models under various assumptions have been done. A good library of theoretical curves for the two layer flat moon and near surface antennas is contained in a Master's thesis by A. P. Annan (Reference 2). Two of his figures are reproduced in Figures 3 and 4 in order to illustrate the nature of the interference pattern to be expected in the simplest cases. Both show relative field strength as a function of transmitter-receiver separation measured in free space wavelengths. Figure 3 shows a typical beat pattern for a half space model. Note that this interference phenomenon is not related to any layering, but merely to the existence of the free space-rock interface. The spacing of the peaks is a function solely of dielectric constant, K, of the material (for low loss materials), and this fact will be used to measure the dielectric constant of the regolith layer on the moon <u>in situ</u> (a secondary objective of the experiment). Figure 4 shows the transition from a half space model to a two layer model (actually a layer over a half space) where the dielectric constant, K_2, of the half space increases from that of the top layer to a very large value. The top curve (K_2=81) represents essentially a perfect reflector. In this figure each curve is scaled so that its initial peak is of constant height (on the figure) and the relative strengths of these peaks are noted above each one. Both Figures 3 and 4 are for a horizontal electric dipole radiating on the interface. Note that the dielectric constant of most powders is 2, ice is 3, most rocks range from 6 to 12, and water is 88.

Figure 4 shows clearly the effect of a good reflecting layer located at a depth of four wavelengths. The peak at $7.5\lambda_0$ gradually increases in amplitude as the dielectric contrast is increased until it is the largest signal received at distances greater than $2\lambda_0$. This peak is an ubiquitous characteristic of models with good reflecting horizons and is due to the specular reflection of the main lobe of the dipole antenna pattern from this horizon.* The intensity of the peak is a function of the contrast in electric properties across the interface while its position in range is determined by the depth to the interface and the dielectric constant of the top layer. For large dielectric contrasts the second order reflection at $15\lambda_0$ can also be seen.

This simple two layer model might be used to model the response of a thick regolith overlying bedrock. Figure 5 (from Reference 3) shows a comparison of such a model with data taken on a glacier (to reproduce the required transparency to radio waves). In this case the top layer is ice and is between 125 m and 200 m thick, as determined by drilling and gravity profiling. The substratum is water saturated rock (a good reflector). The peaks and valleys of the theoretical curve follow the general trend of the data, but in detail there are large discrepancies. Also the calculated depth (114 m) is low. Nevertheless, the presence of the bottom was definitely detected and an estimate of the dielectric constant of the ice could be made. Undoubtedly many of the discrepancies could be resolved with a more complex model - say one that considered side reflections or a sloping bottom to the glacier.

The second problem area that arises in the interpretation of data is that of imperfect data. That is, assuming that a good interpretation can be made given good data, what happens when noisy, uncertain, or inaccurate data must be interpreted? The major uncertainty presently anticipated in the SEP data is the measurement of range, the distance between the transmitter and receiver. The present design of the experiment uses the phase of the 30 Hz modulation to determine the azimuth of the transmitter-receiver line and plans to determine range by using the 1/r fall off of the radiated field strength in regions where reflections are not a major part of the received signal. An independent determination of range at a few points will be available from post-mission analysis of the traverse and the photographic positioning of the geology stops, however the spacing of the preplanned stops will be quite large, on the order of a kilometer. With respect to this problem it should be emphasized that the SEP is intrinsically a profile experiment as opposed to a point measurement experiment.

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*Although a dipole in a homogeneous medium has an isotropic radiation pattern in a plane normal to the axis of the dipole, the vacuum-rock interface acts like a lens and causes the energy radiated into the moon to be modified into a lobate pattern. The main lobe propagates down at an angle Arcsin(1/K).

Spatial frequencies are to be measured and thus the sampling theorem applies. If one wishes to measure a certain frequency then one must sample at least twice that fast. Although the continuous measurement of azimuth will be of some help in evaluating the effect of lateral inhomogeneities and multi-path probelms, it is still essentially an orthogonal coordinate to range and of no direct help in determining distance.

For example, consider the problem of determining K_1, the dielectric constant of the regolith. The spacing of the interference peaks for a simple half space model (with $\tan\delta<<1$) is $(K_1-1)^{-1}$ measured in wavelengths. For $K_1 \simeq 2$ this spacing is about two wavelengths implying that data points must be taken every wavelength at least and more realistically every quarter wavelength. For the higher frequencies (the ones that are applicable to relatively shallow measurements) this means every few meters, clearly a continuous measurement in terms of present plans for rover traverses.

The concept of using the 1/r decay of a radiated signal to determine r is a new one; the method for measuring range originally proposed used a separate radio ranging system similar to present marine radio navigation techniques (Loran). However this method proved difficult to implement on the moon and not accurate enough at large distances. The present concept puts the whole burden of range determination on the analysis phase of the experiment; no additional measurements are made on the moon. Whether this technique will provide adequate range information is speculative. Evaluation in field tests (presently in progress) will be necessary before one can be assured of this. Some improvement in this area could be achieved at a cost of more astronaut time. For example more frequent reporting of the rover odometer range measurement may be needed to insure that range as a function of time can be adequately recovered in the data analysis. Although this measurement is thought to be relatively inaccurate (10%-20%), most of the error is systematic (wheel slip) and may be able to be biased out after some lunar experience with the rover.

Another aspect of the problem of bad data is that of noise, either active (radio sources) or passive (spurious reflections). In this latter category should not be included such effects as reflections off vertical discontinuities or from random inhomogeneities. These are really data - difficult to interpret - but at least lunar in nature. However, reflections from the LM, the rover, or even an astronaut are extraneous and potentially a source of noise. Their small size ($<1\lambda_0$ even at 32 MHz) will tend to minimize their effect of course, but it will be coherent noise (i.e., non-filterable). Preliminary calculations (Reference 4) indicate that reflections from the LM can cause signal influences exceeding 1% (the optimum measurement accuracy). Active sources include impulsive currents (switching transients) in the rover, the LM, the astronaut backpack, other operating experiments (ALSEP, far UV camera, traverse gravimeter), the LCRU with the television camera and remote control unit, and even the CSM when it is overhead. Of these the rover is generally considered to be the largest potential source of interference, and a test of the PLSS/rover/LCRU EMI spectrum is planned for February at MSC (an informal test of the rover alone is also scheduled for November at Boeing, Seattle). However, other man-made sources may also be significant contributors to the ambient noise level on the moon, and less susceptible to test than the rover. The LM, for example, uses an average of 15 amps during the second and third EVA periods, and a variety of thermostated heaters are cycling. The largest of these is the IMU heater which draws 4 amps and has a 25% duty cycle with a period of 20 secs (Reference 5). In addition MESA heaters (6 @ <1 amp) and RCS heaters (32 @ <1 amp) are in automatic thermostated modes during the EVA's with varying on/off periods. The effect of induced signals from these is greatly attenuated, of course, once the receiver is over the horizon from the LM (>5 kms on a smooth moon). However in the region from 2 km to 5 km distant from the LM, the SEP transmitting dipoles will be over the horizon from a 5 foot high receiving antenna while the LM (at an average height of 10 feet) would still be visible. The effect of such a geometry would be to attenuate the desired signal by about 50db over the free space attenuation experienced by the LM noise (Reference 6). A nearer potential noise source is the traverse gravimeter which will be mounted within a meter of the SEP during the traverse and which will have thermostated heaters drawing 50 ma intermittently. Although such a small source will be a very inefficient radiator, its proximity to the reciever makes its effect proportionally greater and simultaneously more difficult to estimate.

Natural sources may also contribute detectible signal levels in this frequency range. The cosmic noise background has recently been measured above the obscuring effects of the ionosphere and has been found to peak around 3 MHz with an effective noise temperature of 10^7°K (Reference 7). The Sun also radiates in the megahertz range and during periods of intense activity can reach 20 to 60 db above the cosmic background. Such periods are infrequent but tend to persist for 2 weeks or more (1/2 a solar rotation). The earth is likewise a radio generator with both continuous and sporadic components. At lunar distances peaks can reach 30db above the background (Reference 8). Such background levels are equivalent to a first stage amplifier noise figure twice the 6db desired.

The net quantitative effect of all these noise sources, however, will depend on the exact wiring configurations and current pulse risetimes for the man-made sources and the region of the sky in view and many random factors for the natural sources. A detailed analysis of the expected noise sources and testing with flight configuration hardware (where possible) is required so that the possible effects on the experiment's results can be evaluated.

IV. CONCLUSIONS

The Surface Electrical Properties Experiment faces three major areas of concern that affect the probability of the experiment meeting its objectives:

1. The effects of relatively complex models of the lunar subsurface to support data analysis and to aid in specifying the measurement accuracy and noise tolerance.

2. The range measurement requirement (both accuracy and degree of continuity) and the technique to be used to implement it, and

3. A comprehensive error analysis.

Of these the last may have an effect on the experiment hardware design and so is the most critical. It should involve an estimation of the noise power spectrum, both continuous and transient, to be encountered on the moon, the end-to-end calibration accuracy of the experiment, the anticipated signal strengths to be measured and the effect of differing lunar models and traverses on these signals. The results of such an analysis may influence the required minimum sensitivity of the experiment, the dynamic range of the field strength measurement, the required measurement accuracy, the transmitter power needed to achieve the above, and other circuit parameters such as bandwidth and amplifier noise figures.

The second area of concern, range measurement, is related to the question of measurement accuracy but the impact of more stringent requirements in this area is less since automatic range measurement has definitely been ruled out. Thus implementation of a new requirement would not involve the hardware development schedule.

The question of theoretical analyses of more complex subsurface models is the least pressing at present and probably the best in hand. Such calculations will primarily be of interest in the interpretation of the returned data, except where effects such as scattering or absorption limit the useful accuracy of the experiment.

M. T. Yates

2015-MTY-kmj

Attachments
References
Figures 1 - 5

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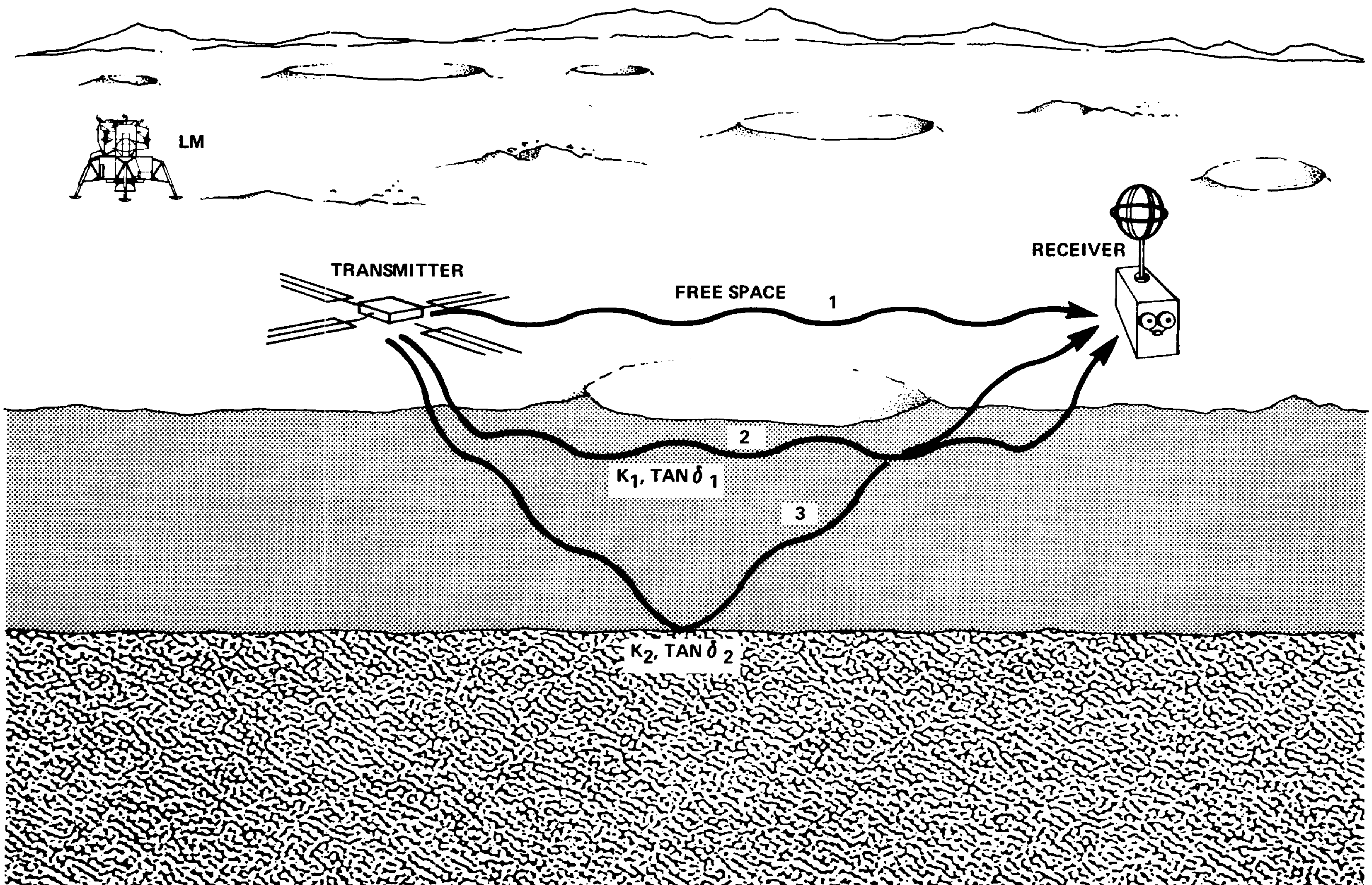

FIGURE 1 – THREE PROPOGATION PATHS FOR A TRANSMITTER OVER A TWO-LAYER MOON.

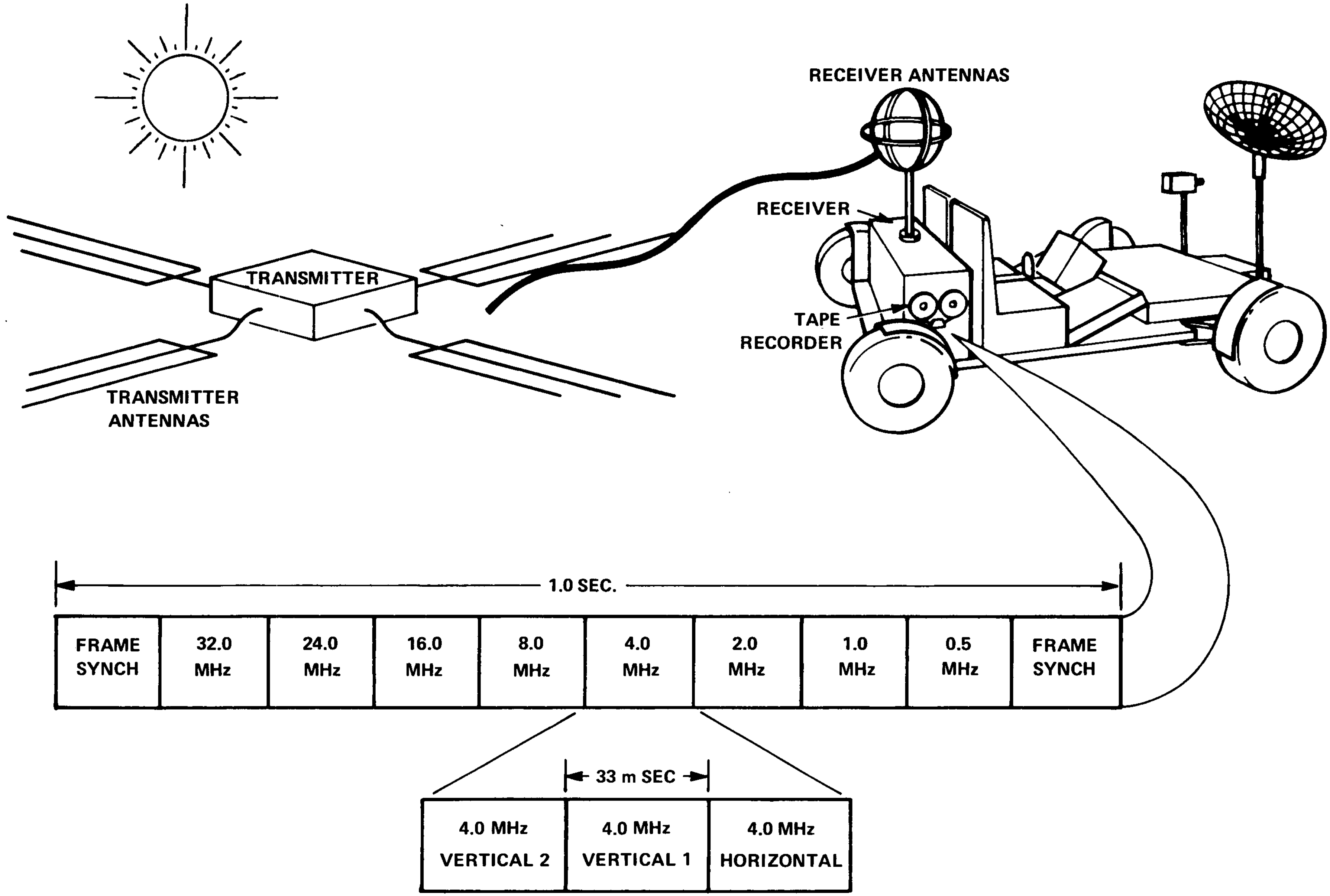

FIGURE 2 - SCHEMATIC DIAGRAM OF SEP HARDWARE AND DATA FORMAT (NOT TO SCALE)

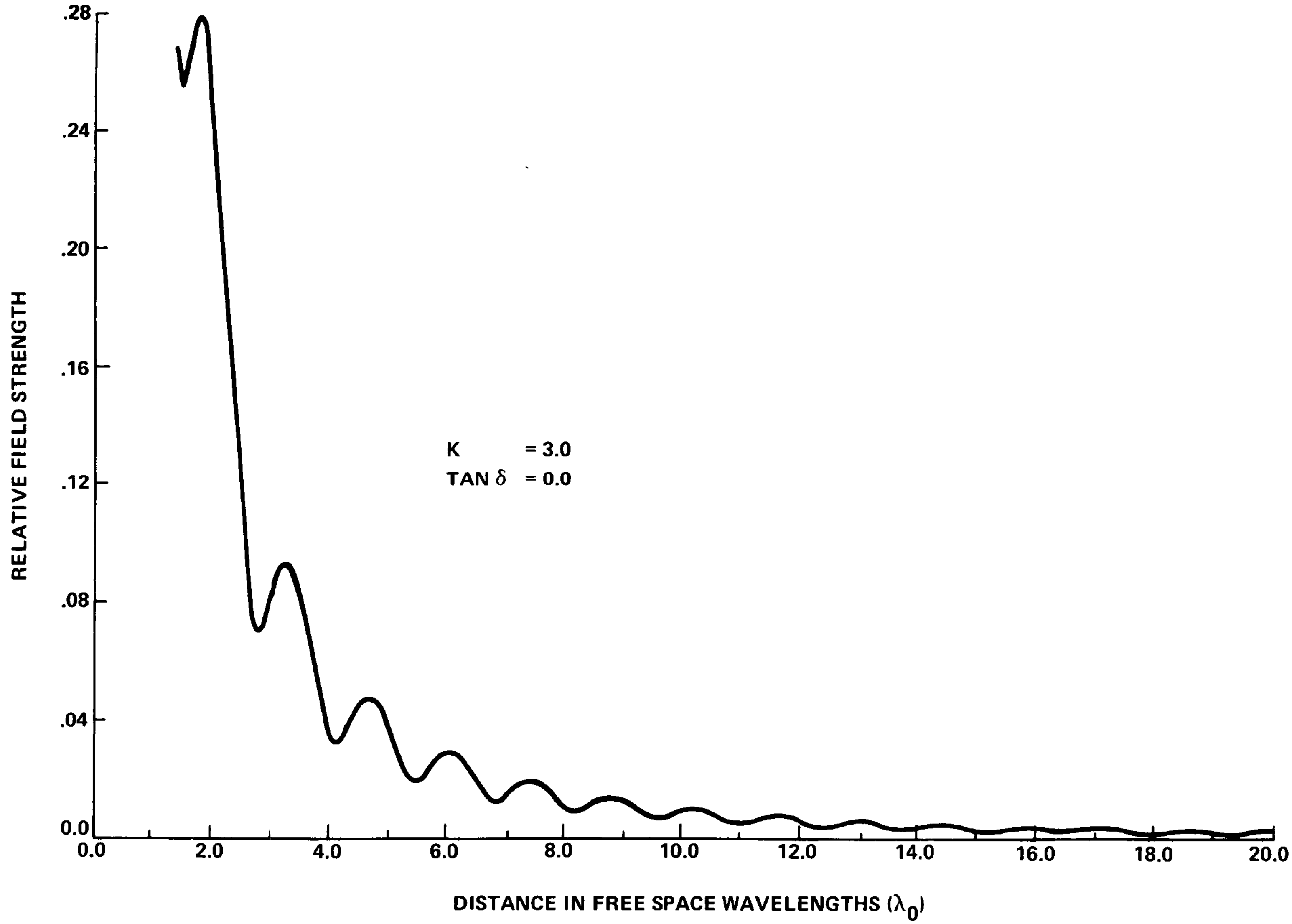

FIGURE 3 - TYPICAL HALF SPACE EARTH PROFILE (AFTER ANNAN)

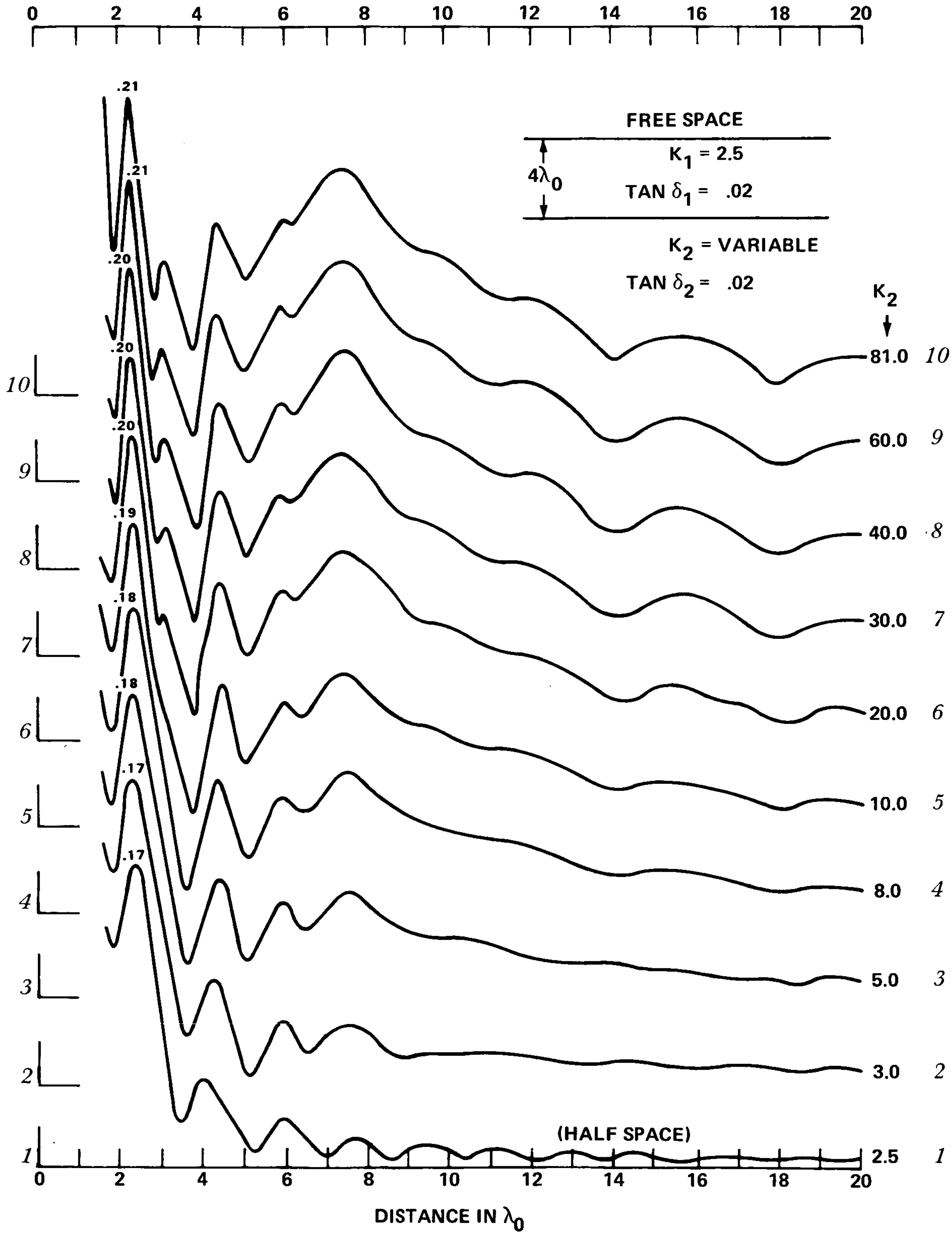

FIGURE 4 - TWO LAYER EARTH PROFILES ILLUSTRATING THE TRANSITION FROM A HALF SPACE TO A PERFECT REFLECTOR. (AFTER ANNAN)

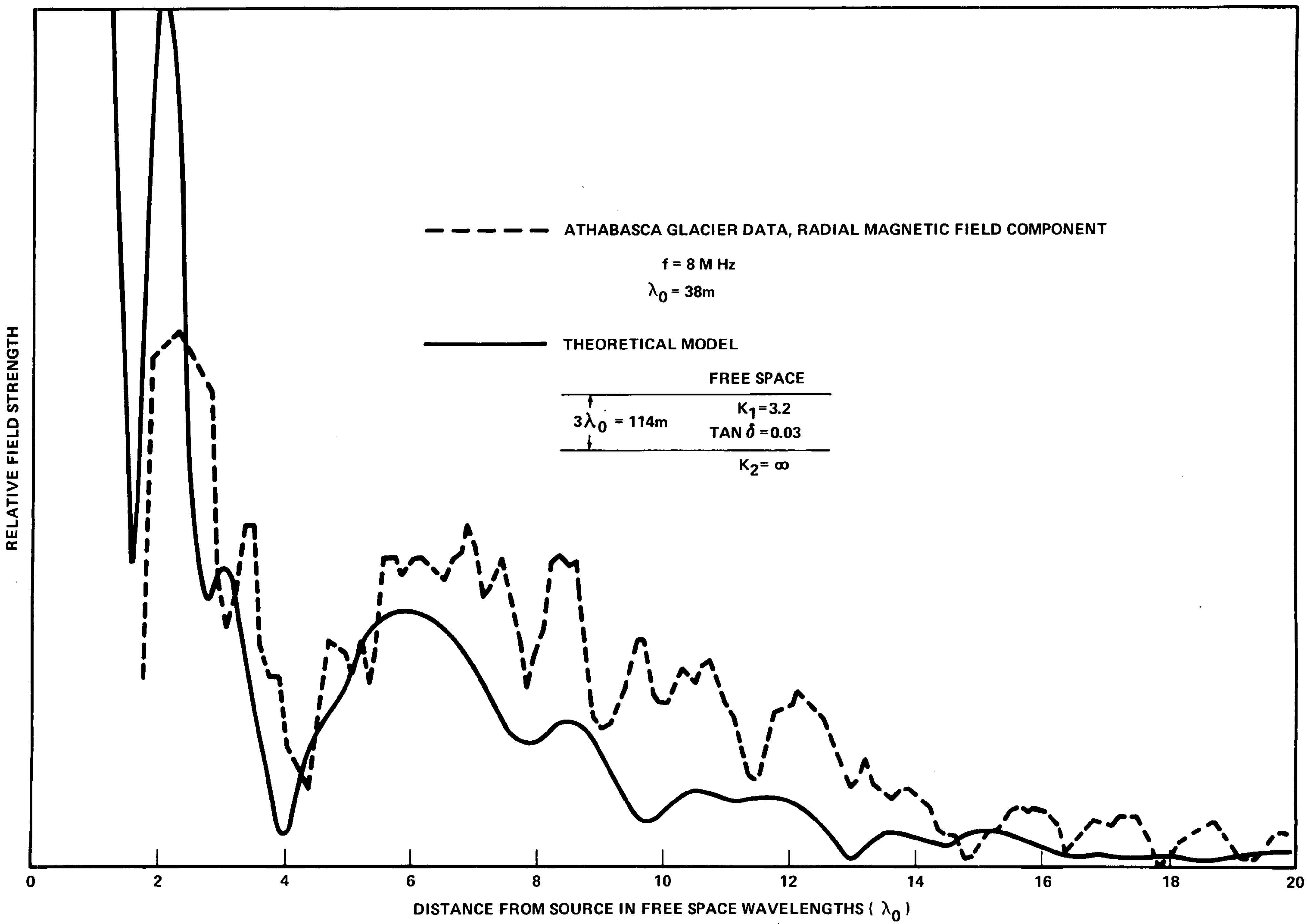

FIGURE 5 – COMPARISON OF THEORETICAL TWO-LAYER MODEL WITH EXPERIMENTAL RESULTS. (FROM REF. 3)

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